REPORT SSD-TR-90-21

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Effects of Neutron Fluence on the Operating Characteristics of Diode Lasers Used in Atomic Frequency Standards

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15 August 1990

Prepared for

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This report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-88-C-0089 with the Space Systems Division, P. O. Box 92960, Los Angeles, CA 90009-2960. It was reviewed and approved for The Aerospace Corporation by J. M. Straus, Director, Chemistry and Physics Laboratory.

Lt. Cynthia Beagle was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) Program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

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7/27/90

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S) TR-0090(5945-05)-3	5. MONITORING ORGANIZATION REPORT NUMBER(S) SSD-TR-90-21
6a. NAME OF PERFORMING ORGANIZATION The Aerospace Corporation Laboratory Operations 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Space Systems Division
6c. ADDRESS (City, State, and ZIP Code) El Segundo, CA 90245	7b. ADDRESS (City, State, and ZIP Code) Los Angeles Air Force Base Los Angeles, CA 90009-2960
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F04701-88-C-0089
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. | WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Effects of Neutron Fluence on the Operating Characteristics of Diode Lasers Used in Atomic Frequency Standards

12. PERSONAL AUTHOR(S) Frueholz, R. P., Camparo, J. C., and Delcamp, S. B. (The Aerospace Corporation); Barnes, C. E. (California Institute of Technology)

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM ________ TO ________	1990 August 15	13

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Atomic clock
Diode lasers
Radiation sensitivities

19. ABSTRACT (Continue on reverse if necessary and identify by block number)
One of the next major advances in rubidium and cesium atomic clock technology will center on the use of diode lasers for optical pumping. The atomic clocks used on board satellites have the potential to interact with various forms of radiation that are not present in the laboratory environment, and the effects of this radiation on the laser's operating characteristics relevant to clock applications are not well known.

The present report describes an ongoing experiment to study the effects of neutron fluence on the operating characteristics of Mitsubishi Transverse Junction Stripe (TJS) AlGaAs diode lasers. Different models of the TJS diode laser produce optical radiation in both the 780 and 850 nm range, appropriate for optical pumping in rubidium and cesium atomic clocks, respectively. In this phase, a set of TJS diode lasers has been exposed to a neutron fluence of 2×10^{12} n/cm^2, and four laser characteristics were examined after each exposure. The laser's light output versus injection current and single-mode linewidth versus output power both influence the efficiency of optical pumping and hence the atomic clock's signal-to-noise ratio. We have also measured the laser's single-mode wavelength versus injection current (laser tuning). Since the diode laser must remain tuned to the appropriate atomic transition, any degradation in the ability to tune the laser will impact atomic clock reliability. Finally, the diode laser's gain curve has been studied at several injection currents below threshold. This diode laser characteristic is taken as an indicator of the neutron damage mechanisms in the laser's semiconductor material. Changes in these characteristics due to the neutron exposure are reported.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) | 22c. OFFICE SYMBOL

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

Contents

Figures

I. Introduction

The next generation of rubidium (Rb) and cesium (Cs) atomic clocks will employ diode lasers for optical pumping to improve their frequency stabilities. It is anticipated that the introduction of laser optical pumping in each of these devices will improve their frequency stabilities by factors of nearly 100 over current designs [1,2]. For space applications, the laser pumped clocks will have to function in the presence of various forms of radiation. In particular, the effects of radiation on diode laser function must be investigated. In this report, we discuss experiments in progress in the laboratories of The Aerospace Corporation to determine the effects of neutron irradiation on the operating characteristics of diode lasers relevant to clock function. The emphasis on characteristics pertinent to atomic clock operation distinguishes this study from previous investigations of neutron effects on diode laser operation [3–5].

Atomic clock operation requires a population imbalance to be established between the two hyperfine levels whose energy difference defines the clock's internal frequency. Optical pumping is a very efficient means of generating the desired population imbalance. The AlGaAs diode lasers [6] are ideal sources of optical pumping radiation. They are compact, solid state devices whose size is attractive for use in the satellite environment. Additionally, they have a number of spectral properties that are well suited to optical pumping in Rb and Cs atomic clocks. The intensities of light they emit are adequate for efficient optical pumping in atomic standards. By varying the mole fraction of Al in these devices, lasers with wavelengths that may be tuned to either Rb or Cs optical resonances are available. Finally, the spectral width of the laser light is sufficiently narrow to allow effective optical pumping in the gas-cell environment of the Rb standard, as well as in the atomic-beam environment of the Cs atomic clock.

Prior to the present studies, the bulk of information concerning the effects of neutron exposure on diode laser operation dealt with the radiation-induced modifications of the diode laser's output power versus injection current curve [3–5]. In the present study, four tests are used to characterize a laser's performance before and after exposure to neutrons. First, the laser's output power versus injection current curve is measured. This characteristic affects the laser optical pumping rate, and hence the signal-to-noise ratio and frequency stability of the atomic clock. This curve also identifies the laser's threshold current, the minimum current at which laser emission takes place. Then the laser's single-mode linewidth versus inverse output power curve is obtained. Again this characteristic influences the efficiency of optical pumping and hence the atomic clock's signal-to-noise ratio. The laser's single-mode wavelength versus injection current curve (laser tuning) is measured. As the injection current is increased, the internal temperature of the lasing media also increases. The increasing temperature causes the lasing wavelength to shift to longer values due to changing of the media's refractive index. As the diode laser must remain

tuned to the appropriate atomic transition, any degradation in the ability to tune the laser will impact the clock's reliability. Finally, the diode laser's gain versus wavelength curve is obtained at several injection currents below threshold. Though this characteristic is not as closely related to atomic clock performance as the others, it is perhaps a better indicator of the neutron damage mechanisms in the laser's semiconductor material. The range of tests encompassed in this study should provide a fuller picture of the effects of neutron exposure on the diode laser characteristics relevant to atomic standard operation.

II. Experimental Procedure

Experimentation is being performed on six Mitsubishi Transverse Junction Stripe (TJS) ML 3101 diode lasers, labeled A through F. The lasers are being characterized at operating temperatures of both 15 and 30°C. Prior to irradiation, the lasers were characterized using the previously mentioned four tests. We found that the lasers divided themselves into two groups. Lasers C and D displayed relatively low threshold currents, approximately 15 mA, while lasers A, B, E, and F showed higher threshold currents, all very near 35 mA. Typically, this type of laser diode has a threshold current near 20 mA, with a maximum of approximately 40 mA. After initial characterization, the lasers were exposed to a neutron fluence of 2×10^{12} n/cm^2 ($E > 1$ MeV) at room temperature at the Sandia Pulsed Reactor (SPR III). The fluence represents the average value of the measurements of three sulfur dosimeters with appropriate corrections applied to convert the dosimeter values to fluences for neutrons with energies greater than 1 MeV.

Upon return to our laboratory, the lasers' optical properties were remeasured. To ensure the reproducibility of our spectral measurements, a control laser, unexposed to neutrons, was also recharacterized. Its spectral properties were required to remain constant prior to proceeding with the characterization of the exposed lasers. In this report, we present the results of this single neutron exposure. We anticipate continuing the study, increasing the exposure to higher neutron fluences.

III. Results

Prior to exposure, all of the diode lasers displayed spectral characteristics consistent with normally behaving devices. After exposure, the two low threshold lasers showed no discernible changes in operating characteristics. In contrast, the four high threshold lasers showed marked changes in their performances. These effects will be reviewed in the following paragraphs.

In Fig. 1, typical output power versus injection current curves are displayed for a low threshold laser (D) and a high threshold laser (E) before and after neutron exposure. No effect of neutron exposure is observed for the low threshold laser. In contrast, laser E shows a slight increase in its threshold current upon neutron exposure. Also, after exposure, this laser can produce no more than 2.4 mW of optical power. The reduced output power could degrade the frequency stability of a clock employing this laser. The behaviors of the two low threshold lasers were consistent, as were the behaviors of the four high threshold lasers. Linewidth versus inverse power curves are presented in Fig. 2 for lasers D and E before and after neutron exposure. The low threshold lasers show no measurable changes due to this exposure. In contrast, the high threshold lasers show increases in their linewidths upon exposure. Again, the potential for changes in linewidth upon neutron exposure would have to be taken into account when considering the application of these lasers in atomic clocks.

Wavelength versus injection current curves for a low threshold laser (D) and a high threshold-laser (E) before and after neutron exposure are displayed in Fig. 3. The apparent changes in laser D's tuning curve upon neutron exposure fall within our normal range of tuning curve reproducibility. Consequently, we cannot state that the radiation exposure had any effect on this laser's tuning. However, laser E displayed a significant change in its tuning characteristics. It is apparent that wavelengths accessible prior to irradiation are no longer attainable after exposure. This could be a serious limitation to the use of this laser in an atomic clock. Again, the two low threshold lasers displayed similar lacks of sensitivity to neutron exposure. Two of the four high threshold lasers were unaffected by the radiation, while the other two showed the effects just discussed.

Review of the diode laser gain curves may give some indication of the origins of the neutron-induced effects. One aspect of the information supplied in these curves is summarized on the graphs shown on Fig. 4. Laser C, representing the low threshold lasers, is unaffected by the neutron exposure. Laser E, a high threshold laser, shows a consistent shift of its gain curve peak to higher energies after neutron exposure. This is somewhat surprising, since the increased threshold currents observed after exposure would indicate increased active region temperature during lasing. Consequently, a shift to lower energies (longer wavelength emission) after neutron exposures would have been expected.

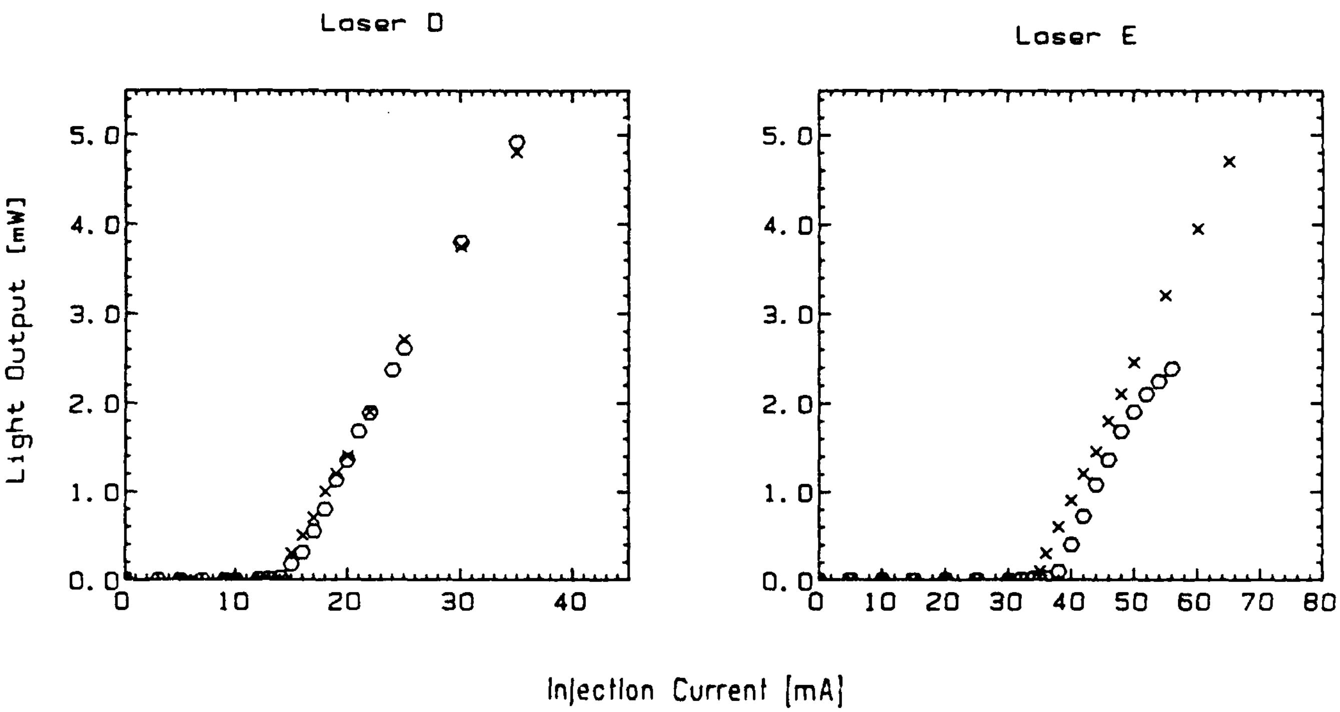

Fig. 1. Output power versus injection current for a low threshold laser (D) and a high threshold laser (E) before (X) and after (○) neutron exposure.

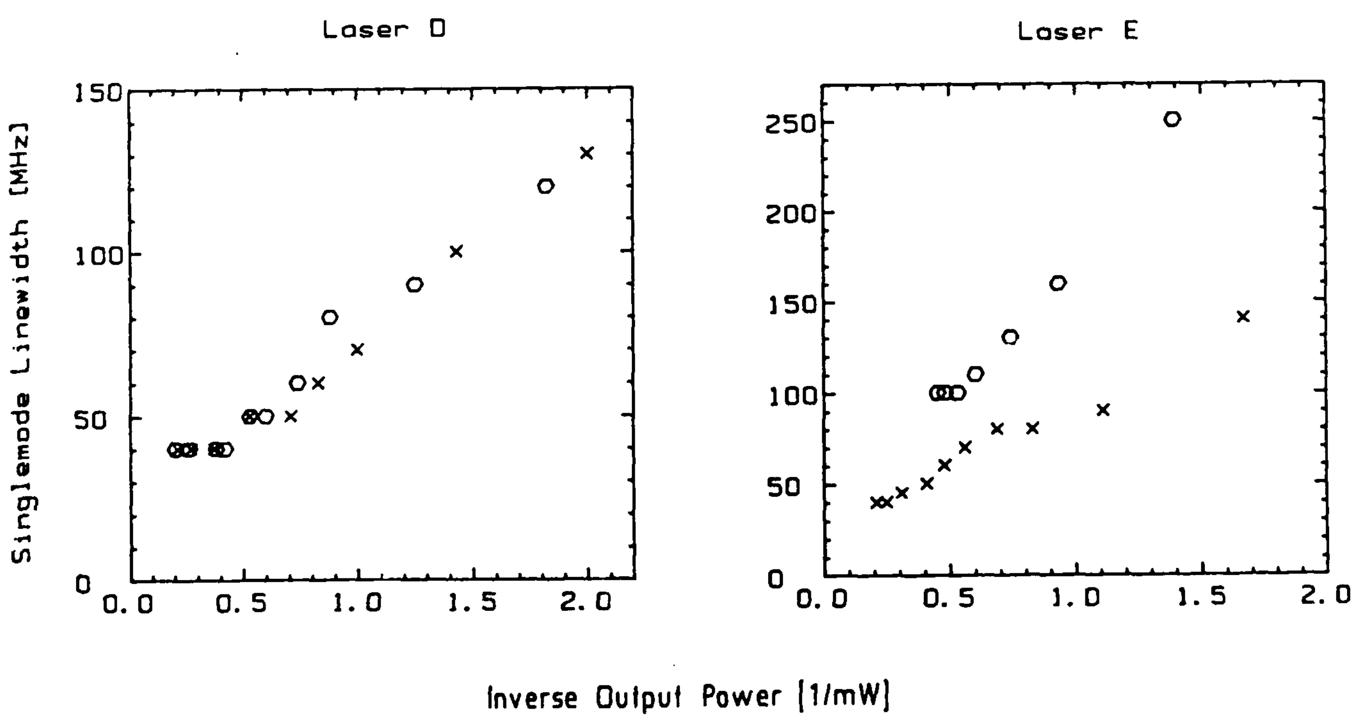

Fig. 2. Linewidth versus inverse power for a low threshold laser (D) and a high threshold laser (E) before (X) and after (○) neutron exposure.

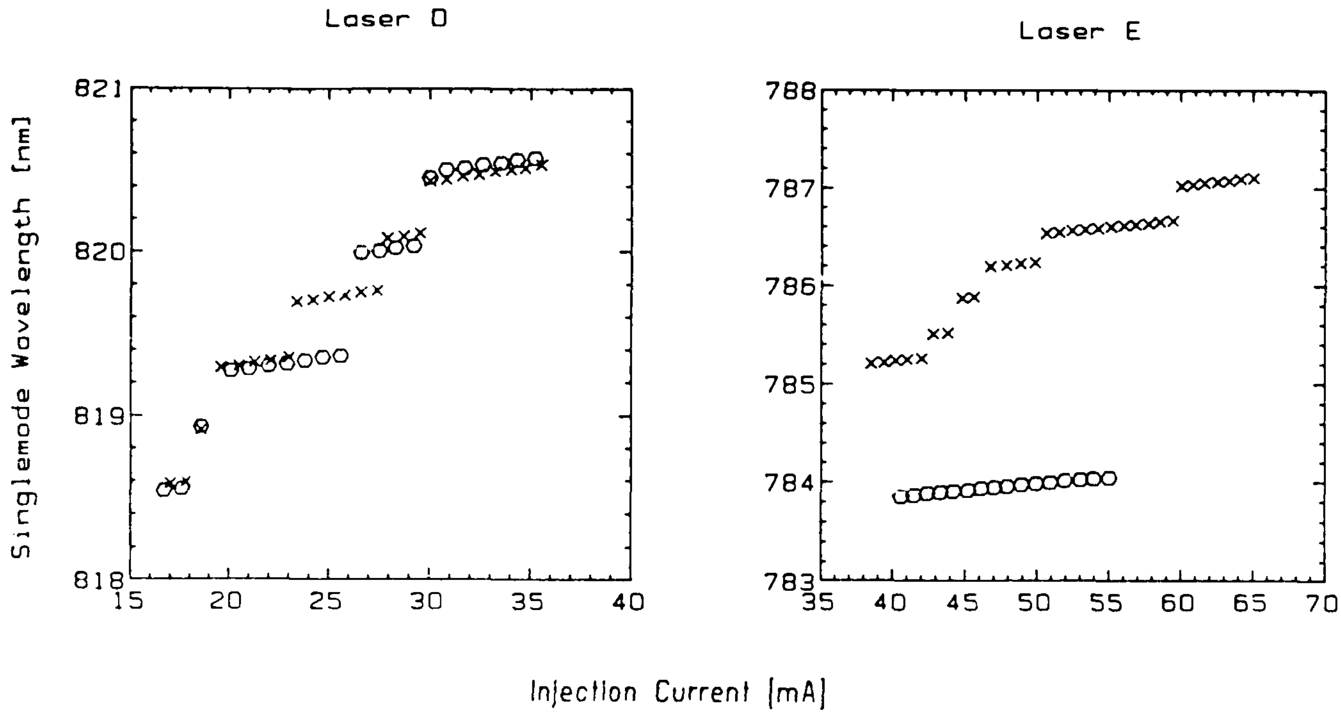

Fig. 3. Wavelength versus injection current for a low threshold laser (D) and a high threshold laser (E) before (X) and after (○) neutron exposure.

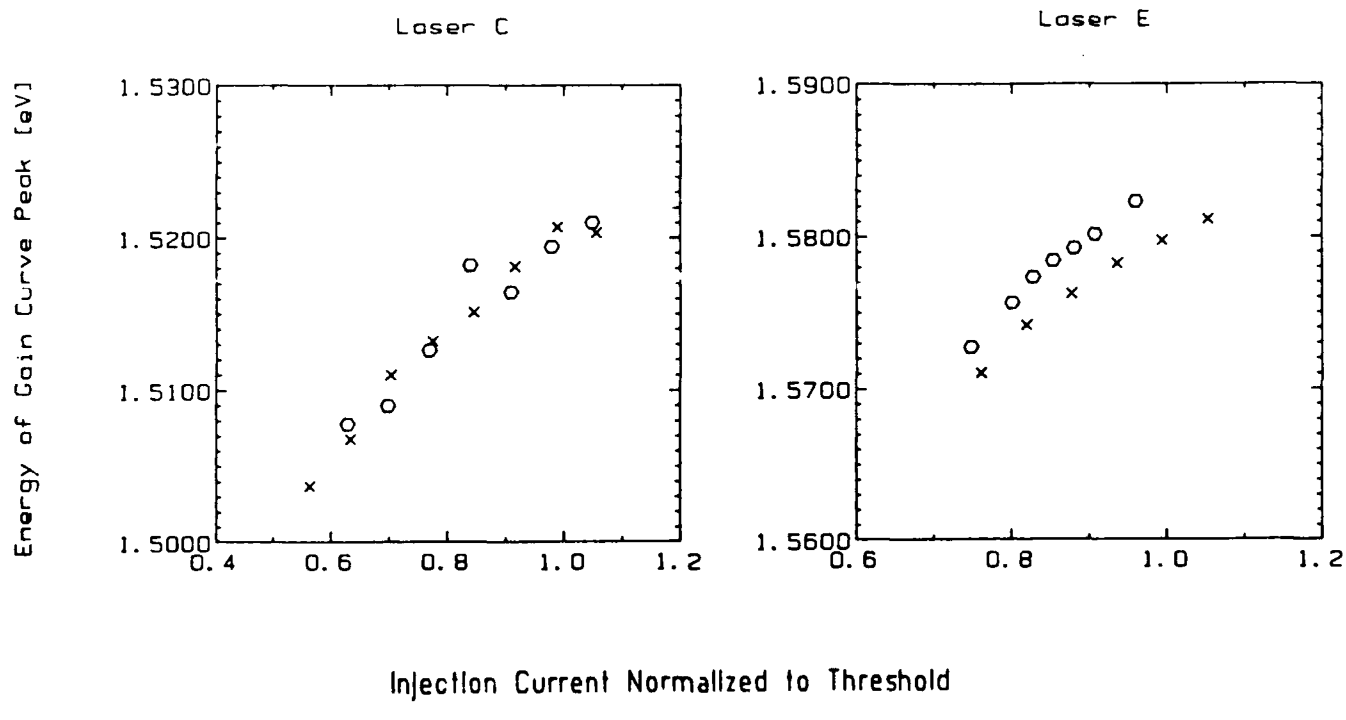

Fig. 4. Energy of gain curve for a low threshold laser (C) and a high threshold laser (E) before (X) and after (○) neutron exposure.

The lack of sensitivity of the low threshold lasers' output power versus injection current curves to this level of neutron exposure is consistent with the findings of Barnes [4]. In the present study, we find that this behavior extends to a range of optical characteristics relevant to optical pumping as would be performed in an atomic clock.

IV. Conclusions

Application of the diode lasers of the type used in this study has the potential to significantly improve the frequency stabilities of the Rb and Cs standards. It is apparent, though, that neutron exposure can lead to tuning curve modifications, increased spectral linewidths, and reduced output powers. Furthermore, these results should extend to AlGaAs diode lasers in general. All of these effects can result in degraded atomic standard performance and potential failure. This is not to say, though, that these devices cannot be used in atomic standards subject to a neutron environment. Rather, if the ultimate operational environment has the potential for neutron exposure, care must be taken in use of the standards. As a first step to reducing a standard's potential sensitivity to neutron exposure, diode lasers with thresholds below typical values should be employed. Additionally, it would be wise to have a laser wavelength control system with sufficient sophistication to correct any small wavelength shifts that might occur upon exposure. To this point, we have addressed the effects of neutron exposure on the operating characteristics of diode lasers at a phenomenological level. With further exposures at increasing fluences and additional analysis, we hope to obtain a more fundamental understanding. Results of this more complete study will be forthcoming.

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LABORATORY OPERATIONS

The Aerospace Corporation functions as an "architect-engineer" for national security projects, specializing in advanced military space systems. Providing research support, the corporation's Laboratory Operations conducts experimental and theoretical investigations that focus on the application of scientific and technical advances to such systems. Vital to the success of these investigations is the technical staff's wide-ranging expertise and its ability to stay current with new developments. This expertise is enhanced by a research program aimed at dealing with the many problems associated with rapidly evolving space systems. Contributing their capabilities to the research effort are these individual laboratories:

Aerophysics Laboratory: Launch vehicle and reentry fluid mechanics, heat transfer and flight dynamics; chemical and electric propulsion, propellant chemistry, chemical dynamics, environmental chemistry, trace detection; spacecraft structural mechanics, contamination, thermal and structural control; high temperature thermomechanics, gas kinetics and radiation; cw and pulsed chemical and excimer laser development, including chemical kinetics, spectroscopy, optical resonators, beam control, atmospheric propagation, laser effects and countermeasures.

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